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Unexpected sites of efficient stochastic acceleration in the inner heliosheath

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Abstract. Up until the recent past, it was generally believed that the solar wind termination shock (TS) is the favourite site to accelerate ions from the keV- to the MeV- energy levels by means of Fermi-1 processes. When Voyager 1 was crossing the TS at the end of 2004, the registrations of this spacecraft showed, however, that beyond the shock passage fluxes of anomalous cosmic rays kept increasing with time. This obviously called for an acceleration site further downstream of the shock in the heliosheath which had not been identified before. In this paper we thus investigate the process of energy diffusion due to wave-particle interactions (Fermi-2) operating on pick-up ions which are convected downstream of the TS with the subsonic solar wind. We investigate the continuous effect of stochastic acceleration processes suffered by pick-up ions at their interaction with heliosheath turbulences, while they are slowly convected with the subsonic solar wind towards the heliotail. As we can show, the inner heliosheath region, with an extent of about 100 AU around the solar wind stagnation point, is specifically favourable for the energy processing of pick-up ions by Fermi-2 processes up to MeV energies. In addition, we claim that this region is the origin of multiply-charged anomalous cosmic ray particles that have been registered in recent times.

Keywords. Interplanetary physics (Cosmic rays; Energetic particles; Heliopause and solar wind termination)

1 Introduction

The crossing of the solar wind termination shock (TS) by Voyager 1 on 16 December 2004 revealed an unexpected behavior of the anomalous cosmic ray (ACR) fluxes, namely just at the location of the TS seen by the Voyager 1 spacecraft, there was no evidence of local acceleration of ACRs (Stone et al., 2005), as predicted. Furthermore, as Voyager 1 moved further downstream from the TS, the intensity of the ACR fluxes continued to increase. Fisk (2005) argues that possibly a source of the ACRs lies ahead of the spacecraft, somewhere in the inner heliosheath. Already before the occurrence of the TS-passage of Voyager 1, Langner et al. (2003) had theoretically recognized that the heliosheath region ahead of the TS acts as a modulation region for galactic cosmic ray (GCR) particles. In particluar, those GCRs with energies below 0.1 GeV are substantially modulated in the heliosheath at their diffusion towards the inner solar system. This process explains an intensity decrease from the heliopause (HP) towards the TS of these middle-energetic particles which perhaps partly may be reflected in the Voyager 1 registrations. The calculations of the above-mentioned authors are, however, sensitive depending on the solar wind velocity profiles which have been artificially adopted (see Langner et al., 2006).

In fact, we show in this paper that charged particles indeed can experience very efficient stochastic (second-order Fermi) acceleration in the nose part of the inner heliosheath located close to the HP. This is due to large exposure times during which the particles suffer these accelerations while slowly being convected towards the heliotail. For the first time this effect was revealed in the calculations by Chalov et al. (2003, 2004), however, in the frame of a quasi-one-dimensional model. We emphasize that we do not consider the acceleration in this region as an alternative to the acceleration of ACRs at the TS, but propose the stochastic acceleration as an additional energization mechanism in the outer heliosphere.

The absence of any indications for the shock-wave acceleration of ACRs at Voyager 1 could be explained, for instance, by an essential nonstationarity of the TS during this time period. There are observational evidences and theoretical calculations showing that the TS, at the moment of the spacecraft crossing, was moving towards the Sun with relatively

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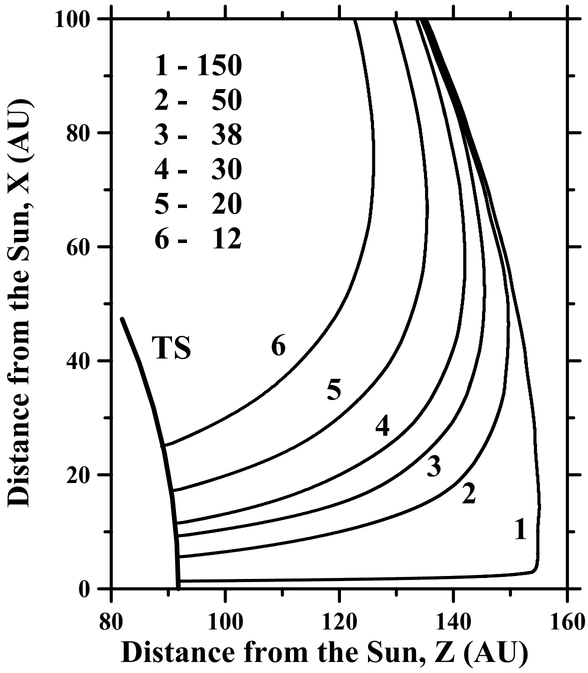

Fig. 1. Streamlines of the plasma flow in the nose part of the inner heliosheath. The HP is traced by the streamline 1 after it passes the stagnation point. The numbers in the upper left part of the figure show the number of a line and the corresponding time T_{conv} (in years), which is needed for a solar wind parcel to move along this streamline away from the TS up to X=100 AU.

high velocity (Decker et al., 2005; Florinski and Zank, 2006). Another explanation is based on the local peculiarity of the relative configuration of the TS and the interplanetary magnetic field (IMF). Due to the relative motion of the Sun and interstellar medium, the shape of the TS is such that the angle between the IMF and shock normal (shock-normal angle) is different at different heliolongitudes. The shock is perpendicular at the nose part and quasi-perpendicular at the flanks. Under such conditions, injection of pick-up ions to the diffusive shock acceleration process is more efficient at the flanks (Chalov, 1993, 2005; Chalov and Fahr, 1996, 2000; Chalov et al., 1997). Voyager 1 crossed the shock not so far from its nose part. When the spacecraft is moving out, it is connected by magnetic field lines to those parts of the shock front that are located closer and closer to the flanks. As a result, the flux of ACRs can increase (McComas and Schwadron, 2006). Furthermore, the origin of multiply-charged ACRs which have been observed is briefly discussed.

2 The plasma flow pattern in the upwind part of the inner heliosheath

The HP is the boundary separating the solar wind and interstellar plasma. Since the solar wind is supersonic, it passes through a shock (TS) before it meets the HP. Although the solar wind speed, number density and temperature depend on the heliolatitude, the flow of the solar wind in the supersonic regime can be considered as quasi-one-dimensional, i.e. the deviation of the flow lines from straight lines is only weakly pronounced. The solar wind flow in the inner heliosheath, in comparison, is essentially three-dimensional, since it cannot pass through the HP but must flow tangential to it, feeling the obstacle by pressure gradients. Typical streamlines of the solar wind in the nose part of the inner heliosheath are shown in Fig. 1. The streamlines were calculated in the frame of the axi-symmetric, multi-component model of the solar wind interaction with the local interstellar medium (Malama et al., 2006). In this figure the Z-axis is directed towards the interstellar wind flow and the x-axis is in a transverse direction. The TS is shown as the solid line, while the HP is rather precisely traced by streamline 1 behind the stagnation point. The numbers in the upper left part of the figure show the number of a line and the corresponding convection time T_{conv} (in years), which is needed for a solar wind parcel to move along this streamline away from the TS up to some distance (in our case at x=100). This distance is restricted by the off-axis angle about 45°. It is evident from these results that the plasma flow in this region is very slow and energetic particles (pick-up ions) co-moving with solar wind plasma can experience stochastic acceleration during very extended periods of time (up to 150 years). Even if the level of turbulence is low in the inner heliosheath one can expect, nevertheless, that particles can be processed under such conditions up to high energies.

In the inner parts of the heliosphere stochastic acceleration of pick-up ions is compensated to some extent by adiabatic cooling in the radially divergent supersonic flow. In this respect, the nose part of the inner heliosheath is completely different and the ideal place for such type of acceleration, since velocity divergence in this region is negative, as one can see in Fig. 2. This figure shows dimensionless velocity divergences ($\text{div}^*\boldsymbol{V}=r_{\text{E}}\,\text{div}\boldsymbol{V}\,/\,V_{\text{SW,E}}$), normalized to the solar wind velocity at 1 AU ($V_{\text{SW,E}}$=430 km s^{-1}) and r_{E}=1 AU as functions of the off-axis angle. The divergence distributions are shown along the TS (downwind of the shock) and along the HP (inside of the HP). The values of divergence in the entire inner heliosheath are between these two extreme distributions. These values have very small magnitudes as compared with the divergence at 1 AU (=2) but it is very important that they are negative, thereby leading to adiabatic heating. It means that they operate in the same direction as stochastic acceleration.

3 Stochastic acceleration efficiency in the heliosheath

To estimate the efficiency of the stochastic acceleration rate by means of wave-particle interactions in the inner heliosheath, for the sake of simplicity, we restrict our consideration to Alfvénic turbulence, though there are observational evidences that compressible turbulence is also prominent just downstream of the TS (Burlaga et al., 2006). The relative role of compressible fluctuations in the acceleration process will be discussed at the end of this section. Note also that if we consider pick-up ions in the heliosheath, the more abundant and energetic population which is present in this region was created in the supersonic solar wind (Malama et al., 2006). Thermal velocities of pick-up ions from this population in front of the TS were equal approximately to the supersonic solar wind speed. After crossing of the TS the thermal velocities increase due to growth in the magnetic field strength, so these particles are sufficiently energetic to suffer stochastic acceleration. Although in the vicinity of the TS the pitch-angle distribution of pick-up ions can be highly anisotropic, it can relax rather quickly to a nearly isotropic distribution in the inner heliosheath (Chalov and Fahr, 2000).

According to Fisk (1976) the characteristic time for acceleration of particles of energy E by Alfvénic turbulence can be written as

$$T_{\rm acc} = 2\kappa_{\parallel}/v_{\rm A}^2\,, \tag{1}$$

where $\kappa_{\parallel}=v\Lambda_{\parallel}/3$ is the parallel diffusion coefficient, $\Lambda_{\parallel}$ is the parallel mean free path, $v_{\rm A}$ is the Alfvén speed, and v is the particle speed. The maximum rate of acceleration occurs when the scattering mean free path $\Lambda_{\parallel}$ is set equal to the local cyclotron radius $r_{\rm g}$ (so-called Bohm limit). Let us introduce a parameter η, which will be considered as a constant:

$$\eta = r_{\rm g}/\Lambda_{\parallel}\,. \tag{2}$$

The parameter describes the efficiency of scattering of charged particles by Alfvénic turbulence. Strong scattering corresponds to $\eta\cong 1$, while at $\eta\ll 1$ scattering is weak. Then the acceleration time can be rewritten as

$$T_{\rm acc} = 2vr_{\rm g}/3\eta v_{\rm A}^2\,. \tag{3}$$

Thus, we must estimate the values of $r_{\rm g}$ and $v_{\rm A}$ in the inner heliosheath. Let us adopt that the TS is located at 100 AU and the compression at the shock equals 3. The compression corresponds to the measured value of the magnetic field increase (3.05±0.04) during the Voyager 1 crossing of the TS (Burlaga et al., 2005, 2006). Although the measured distance to the TS is 94 AU, small variations (±10 AU) do not influence our estimations. Then taking the nominal value for the IMF, B, at 1 AU and taking a $B\propto r^{-1}$ dependence, one can find that just downstream of the shock

$$r_{\rm g}\,({\rm TS}) = 0.95\times 10^{11}\,(AE)^{1/2}\ \ {\rm cm}\,, \tag{4}$$

where A is the atomic number of the ion and E is the energy in MeV. The value of the magnetic field changes from the TS to the HP. At present, the spatial behavior of the magnetic field in the inner heliosheath is not known precisely, however, it is believed that the magnetic field increases when approaching the HP. According to kinematic models (see, e.g. Zank, 1999), the magnetic field suffers an approximately eightfold increase in the magnitude from the TS up to the heliopause along the stagnation line. Self-consistent models (e.g. Pogorelov et al., 2006) give a smaller increase (about 3 times). For our estimations we assume that the magnetic field averaged over the heliosheath is larger than that one just behind the TS by a factor of σ ($\sigma\geq 1$), which is a free parameter. Then the averaged cyclotron radius in the heliosheath is

$$r_{\rm g}({\rm HS}) = 0.95\times 10^{11}\,(AE)^{1/2}/\sigma\ \ {\rm cm}\,. \tag{5}$$

To estimate the value of the Alfvén speed, we assume that it is constant in the supersonic solar wind (=40 km s^{-1}) and in the inner heliosheath, but at the TS it increases by the factor $s^{1/2}$, where s is the compression at the shock (s=3 in our case). Then we obtain finally for the acceleration time in the inner heliosheath:

$$T_{\rm acc} = 0.06E/\sigma\eta\ \ {\rm years}\,. \tag{6}$$

The energy is usually expressed in MeV per nucleon. However, this would lead to the appearance of the additional parameter A in Eq. (6).

Figure 3 shows the acceleration times (in years) for particles to reach 1 MeV and 10 MeV for different values of the pitch-angle scattering rate η. Two different cases for the magnetic field behavior in the inner heliosheath are presented: 1) the averaged magnitude of the magnetic field equals the magnitude of the field just behind the TS (σ=1), 2) the averaged magnitude is 5 times larger than the magnitude just behind the TS (σ=5). If we compare the acceleration times and the convection times presented in Fig. 1, we can conclude that pick-up protons can be accelerated in the upwind part of the inner heliosheath up to 10 MeV even under weak scattering conditions (η=0.01). Regarding pick-up oxygen, the corresponding acceleration time (up to the same energy per nucleon) is larger by a factor of 16. It means that oxygen pick-up ions can be accelerated up to 10 MeV/nuc only in the case of a high or medium scattering rate ($\eta\geq 0.1$)

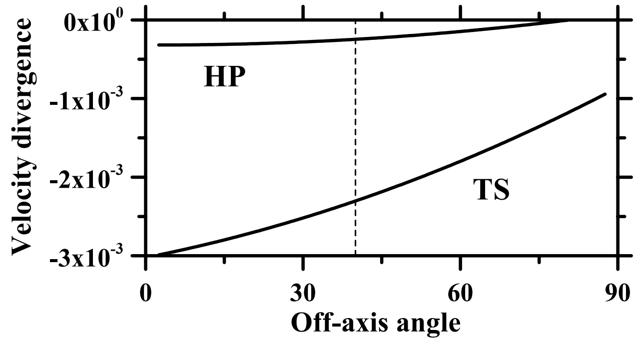

Fig. 2. Normalized velocity divergence in the inner heliosheath just downstream of the TS and along the inner side of the HP as functions of the off-axis angle. The angle values below the dashed line corresponds to the region shown in Fig. 1.

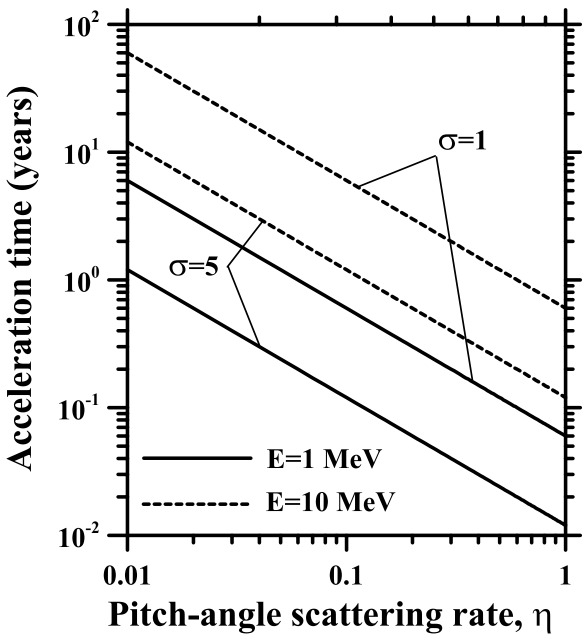

Fig. 3. Acceleration time for 1 MeV (solid lines) and 10 MeV (dashed lines) energies as a function of the pitch-angle scattering rate for different values of σ.

or in the case when the magnetic field magnitude substantially increases in the heliosheath ($\sigma \geq 5$) compared to its value near the TS.

The measurements of the magnetic field just behind the TS show that compressible fluctuations are possibly dominating in this region (Burlaga et al., 2005, 2006). In fact, the properties of solar wind turbulence in the inner heliosheath are absolutely unknown. Therefore, although detailed calculations of energy diffusion coefficients of energetic particles interacting with compressible fluctuations are available at present (see, e.g. le Roux et al., 2005), we will use a simple qualitative consideration to compare efficiencies of stochastic acceleration by Alfvénic and compressible turbulences in the inner heliosheath. If $T_{\rm acc}^{\rm (compr)}$ is the characteristic time for acceleration by compressible turbulence, then we can write (Fisk et al., 2000):

$$\frac{T_{\rm acc}^{\rm (compr)}}{T_{\rm acc}} \sim \left(\frac{B}{\delta B}\right)^2 \frac{L_\perp^2}{L_\parallel \Lambda_\parallel} \sim \left(\frac{B}{\delta B}\right)^2 \frac{r_{\rm g}}{L_\parallel}\,\eta\,, \tag{7}$$

where δB is the fluctuation of the magnetic field magnitude, $L_\perp$ and $L_\parallel$ are the characteristic scale lengths of fluctuations perpendicular and parallel to the mean field, respectively. Fisk et al. (2000) argue that $L_\perp \sim r_g$ in the solar wind. This relation is taken into account in the last expression in Eq. (7). According to Burlaga et al. (2006), $\delta B/B \approx 0.3$ behind the TS, so the first factor in Eq. (7) is about 10. However, $\eta<1$ (and even $\eta \ll 1$) and most likely that $r_{\rm g}/L_\parallel \ll 1$. Thus, $T_{\rm acc}^{\rm (compr)}$ can be considerably smaller than $T_{\rm acc}$. This circumstance only supports the main idea of the present paper.

4 Origin of multiply charged ions in the inner heliosheath

Measurements of ACRs near the Earth's orbit revealed the presence of multiply-charged nitrogen, oxygen, and neon ions with ionic charge states of 2, 3, and higher (Mewaldt et al., 1996; Klecker et al., 1998). Furthermore, at energies larger than 20–25 MeV/nuclon the multiply-charged components are dominant. On the basis of numerical simulations, Jokipii (1996) argued that further ionization of singly charged oxygen through the electron stripping process occurs during the acceleration at the TS. From the above discussion it appears that electron stripping, i.e. atom impact ionization, can also be very effective in the nose part of the inner heliosheath. We, however, do not consider here this process, which is of importance at high energies, and restrict our consideration to electron impact ionization of pick-up oxygen at keV-energies.

While singly-charged pick-up ions, e.g. O^+, are slowly convected with the subsonic solar wind within periods of about 50–100 years over the active region near the stagnation point, they are not only subject to stochastic acceleration processes, but also to electron impact ionization processes. Since solar wind electrons in the heliosheath region have energies of the order of 1 keV, they in fact can effectively ionize O^+ ions which have an ionization energy of 35.11 eV. The doubly charged O^{++} ions can then be further processed up to energies at which their mean free scattering path length becomes large enough so that these ions are no longer tightly bound to the solar wind plasma flow, but can diffuse freely through the heliosheath region until they reach the TS. Here they then can undergo the process of Fermi-1 acceleration till they finally arrive at energies which are typical for ACRs ($\geq$10 MeV/nuc).

An estimation for the abundance of O^{++} ions, due to ongoing electron impact ionizations of O^+ ions, can be made on the basis of the following system of equations:

$$\frac{{\rm d}n\left(O^{++}\right)}{{\rm d}t} = \beta_{\rm e} n\left(O^+\right)\,, \quad \frac{{\rm d}n\left(O^{+}\right)}{{\rm d}t} = -\beta_{\rm e} n\left(O^+\right)\,, \tag{8}$$

where $\beta_{\rm e}$ is the electron impact ionization rate. Let us assume that the solar wind plasma after the passage over the TS behaves fairly incompressible and has a downstream electron density of $n_{\rm e}\,({\rm HS}) \simeq 1.5\times10^{-3}\,{\rm cm}^{-3}$ and a temperature of $E_{\rm e}=kT_{\rm e}\simeq 0.75$ keV. Then by adopting a Maxwellian distribution for the electrons we will have the following ionization rate for single ionization by electron impact (Lotz, 1967):

$$\beta_{\rm e}^{\rm s}\left({\rm O}^+ \to {\rm O}^{++}\right) = 3.15\times10^{-8}{\rm s}^{-1}\,. \tag{9}$$

The total ionization rate is given by

$$\beta_{\rm e} = n_{\rm e}\,({\rm HS})\,\beta_{\rm e}^{\rm s}\left({\rm O}^+ \to {\rm O}^{++}\right) = 4.73\times10^{-11}{\rm s}^{-1}\,. \tag{10}$$

Now by solving Eqs. (8), one can estimate the abundance ratio of doubly charged over singly charged ion species by

$$\frac{n\left(\mathrm{O}^{++}\right)}{n_0\left(\mathrm{O}^{+}\right)} = 1 - \exp\left(-\beta_{\mathrm{e}} T_{\mathrm{conv}}\right) , \tag{11}$$

where T_{conv} is the time the convected ion has spent in the stagnation region of the heliosheath and $n_0\left(\mathrm{O}^{+}\right)$ is the initial number density of singly charges ions (just behind the TS). Then we obtain for T_{conv}=50 years:

$$n\left(\mathrm{O}^{++}\right)/n_0\left(\mathrm{O}^{+}\right) \approx 0.07\,. \tag{12}$$

5 Conclusions

We show in this paper that the nose part of the inner heliosheath is the ideal place for stochastic acceleration of charged particles up to energies of the order of 10 MeV/nuc, due to large exposure times during which the particles suffer the acceleration while slowly being convected towards the flanks of the heliosheath. It is also important that the velocity divergence in this region is negative. It means that in this region adiabatic heating exists rather than cooling, as in the supersonic solar wind. Note that, for the first time, the fact that stochastic acceleration of pick-up ions near the stagnation point in the inner heliosheath can effectively produce high-energy particles was predicted in the calculations by Chalov et al. (2003, 2004). This prediction is now supported and put on a more general basis, although a comprehensive numerical simulation is needed to obtain precise energy distributions and number densities of accelerated particles. The numerical model should adequately describe the escape of energetic particles from the acceleration region due to a large mean free path. Of course, this escape reduces the efficiency of stochastic acceleration in the inner heliosheath, however, it allows energetic particles to reach the TS where they can suffer further shock-drift or diffusive acceleration.

Due to electron impact ionization and the electron stripping process, multiply-charged ions can originate in the inner heliosheath and in fact reach abundances of a few percents with respect to singly-charged ions.

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